Development of an Ultra-Wideband Receiver for the North America Array

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ABSTRACT. — The North America Array (NAA) is a concept for a radio astronomical interferometric array operating in the 1.2 GHz to 116 GHz frequency range. It has been designed to provide substantial improvements in sensitivity, angular resolution, and frequency coverage beyond the current Karl G. Jansky Very Large Array (VLA). It will have a continuous frequency coverage of 1.2 GHz to 50 GHz and 70 to 116 GHz, and a total aperture 10 times more sensitive than the VLA (and 25 times more sensitive than a 34-m-diameter antenna of the Deep Space Network [DSN]). One of the key goals for the NAA is to reduce the operating costs without sacrificing performance. We are designing an ultra-wideband receiver package designed to operate across the 8–48 GHz frequency range in contrast to the current VLA, which covers this frequency range with five receiver packages. Reducing the number of receiving systems required to cover the full frequency range would reduce operating costs. To minimize implementation, operational, and maintenance costs, we are developing a receiver that is compact, simple to assemble, and that consumes less power. The objective of this work is to develop a prototype integrated feed-receiver package with a sensitivity performance comparable to current narrower-band systems on radio telescopes and the DSN, but with a design that meets the requirement of low long-term operational costs. The ultra-wideband receiver package consists of a feedhorn, low-noise amplifier (LNA), and downconverters to analog intermediate frequencies. Both the feedhorn and the LNA are cryogenically cooled. Key features of this design are a quad-ridge feedhorn with dielectric loading and a cryogenic receiver with a noise temperature of no more than 30 K at the low end of the band. In this article, we report on the status of this receiver package development, including the feed design and LNA implementation. We present simulation studies of the feed horn carried out to optimize illumination efficiencies across the band of interest. In addition, we show experimental results of low-noise 70-nm gallium arsenide, metamorphic high-electron-mobility-transistor (HEMT) amplifier testing performed across the 1–18 GHz frequency range. Also presented are 8–48 GHz simulation results for 35-nm indium phosphide HEMT amplifiers.

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

I. Introduction

The North America Array (NAA) is a concept for a next-generation radio telescope array operating in the 1.2 GHz to 116 GHz frequency range.[1] It will consist of approximately 300 antennas with baselines extending to 300 km. The NAA is expected to have continuous frequency coverage of 1 GHz to 50 GHz and 70 GHz to 116 GHz, and a total aperture 25 times more sensitive than a 34-m-diameter antenna of the Deep Space Network (DSN). JPL is in a unique position both to enable the NAA and to benefit from it. With its frequency coverage, the NAA would cover all the deep-space communication frequency allocations and all the planetary radar frequency allocations. We should point out that the NAA is also known as the next-generation VLA. Figure 1 shows a plot of effective collecting area as a function of frequency for various telescopes. Note that the NAA (NextGen VLA) will have 10 times the collecting area of the Karl G. Jansky VLA (JVLA) and the Atacama Large Millimeter-wave Array (ALMA).

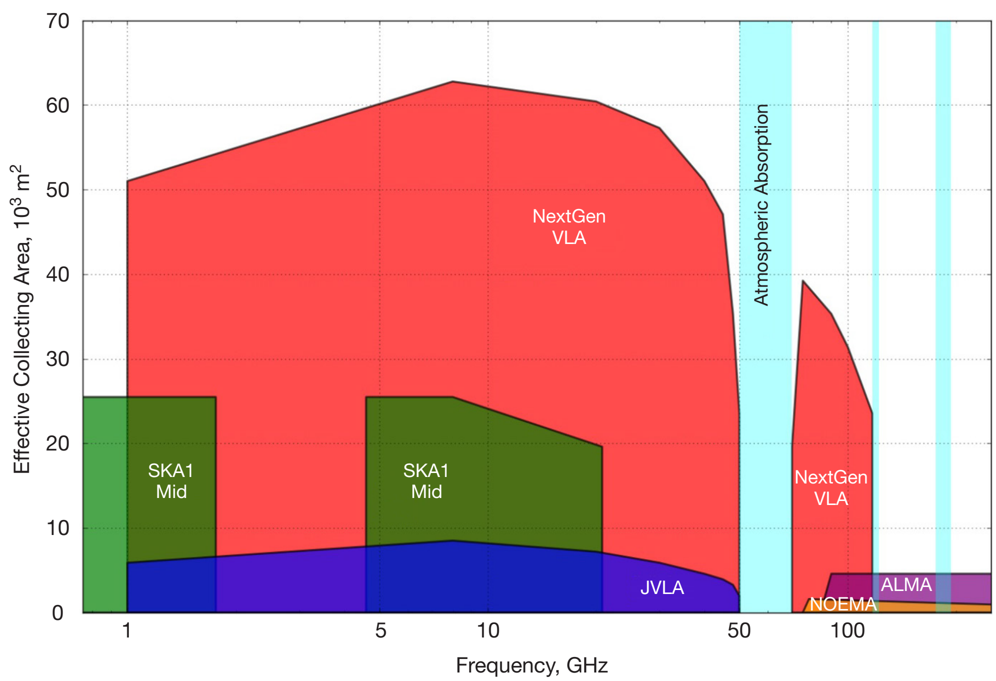

Figure 1. Plot showing effective collective area as a function of frequency for various telescopes. (SKA = Square Kilometre Array; NOEMA = Northern Extended Millimeter Array)

The effort we are reporting here focuses on the development of a prototype ultra-wideband feed-receiver package for the NAA. Much like the case for the DSN, operational costs are increasingly recognized as a factor in determining the viability for current and future radio telescopes. For the NAA to achieve the required sensitivity, the feed-receiver systems will have to be cryogenically cooled, but in order to minimize operational costs associated with the cryogenics, the number of such feed-receiver systems should be minimized. Similarly, integrated and easily serviceable feed-receiver systems are expected to reduce maintenance costs and downtime. These considerations lead us to target the development of a single, integrated, cryogenically cooled feed-receiver package with a continuous instantaneous

[1] National Radio Astronomy Observatory, "Next Generation Very Large Array," https://science.nrao.edu/futures/ngvla

frequency coverage of 8–48 GHz that delivers a sensitivity performance comparable to current narrower-band systems on radio telescopes and the DSN. The aforementioned receiver should be low cost, easy to manufacture, and easy to service. In concert with other researchers from other organizations developing systems at lower frequencies, we would demonstrate that key components of the NAA are sufficiently mature in time for the 2020 Astronomy Decadal Survey.

The DSN and current radio telescope receiving systems define the state of the art in receivers. DSN receivers have extremely low system temperatures, typically 25 K or better, but in fairly narrow bands (mostly at S-, X-, and Ka-bands) with typical bandwidths no larger than 10 percent [1]. The VLA, operated by the National Radio Astronomy Observatory (NRAO), employs five different receiving systems that mostly cover the 8–48 GHz frequency range (8–10 GHz, 13–15 GHz, 20.2–22.2 GHz, 31–33 GHz, and 40–42 GHz). These systems have typical receiver temperatures of 25 K or so over octave or narrower bandwidths. By contrast, our proposed ultra-wideband receiving system design will allow a slight decrease in the sensitivity requirement in order to obtain a much larger frequency coverage and lower associated long-term operational costs.

In this article, we present initial preliminary design results of the ultra-wideband receiver package. We report on the design of a wideband feed and wideband monolithic microwave integrated circuit (MMIC) low-noise amplifiers (LNAs) from the foundry OMMIC. We also include initial design results of LNAs from Northrop Grumman Corporation, and conclude with an initial analysis of noise temperature performance of the entire ultra-wideband receiver package.

II. Description

The ultra-wideband receiver package under development will have direct application in the eventual implementation of the NAA. The receiver we are designing will allow us to assess whether wideband operation in the 8–48 GHz range can be achieved with a single receiver while meeting the desired receiver gain and noise temperature performance. In addition, the planned construction and testing of our receiver will provide valuable information about receiver cost and power consumption, as well as operational costs. All this information will have direct impact in conceptualizing the NAA.

The ultra-wideband receiver package, shown schematically in Figure 2, includes a feed, LNAs, and a downconversion stage (the feed and LNA are cryocooled). Responding to the combination of scientific and operational considerations, our design goals for the receiver system are:

(1) Continuous frequency coverage of 8–48 GHz.

(2) Downconversion stage with multiple bands, providing an intermediate frequency whose value is dependent on the number of bands selected.

(3) System noise temperature of <35 K across each of the intermediate bands.

(4) 30 dB gain across each of the intermediate bands.

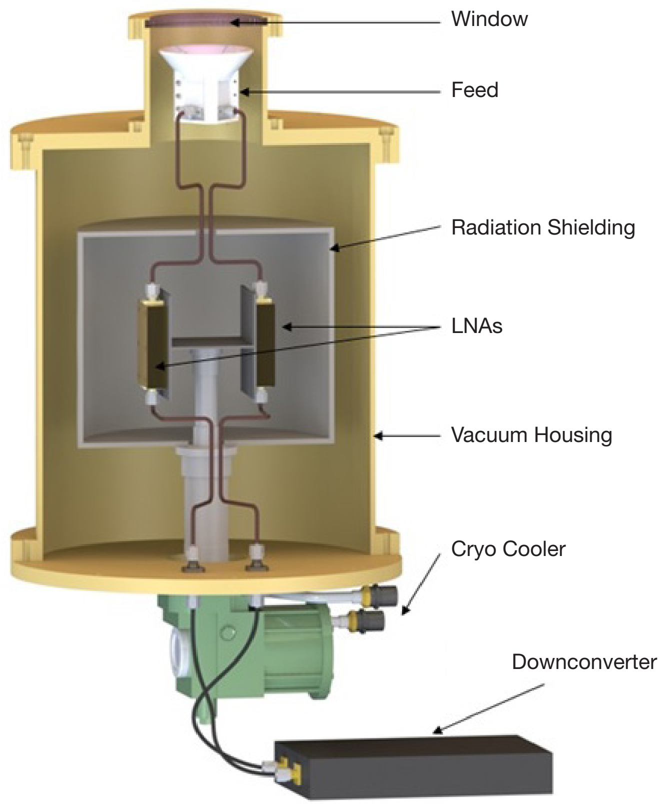

Figure 2. Layout of ultra-wideband receiver showing its various parts.

The resulting integrated, cryogenically cooled feed-receiver package will have a sensitivity performance comparable to current narrower-band systems on radio telescopes and the DSN but with a design that responds to the requirements of lower long-term operational costs.

III. Feed Design

For the ultra-wideband receiver package, we are considering a single feed, capable of operating in the 8–48 GHz frequency range (6:1 frequency ratio). The wideband feed that we are considering for this project is a scaled version of the quad-ridge flared horn antenna model QRFH-HA-6-FL developed by Sander Weinreb's Microwave Research Group.[2] The QRFH-HA-6-FL horn is designed to operate in the range of 3 GHz to 18 GHz, but the design concept can be scaled to allow for efficient illumination of microwave reflector antennas over a frequency range of F_L to $6F_L$ GHz, where F_L is the lowest frequency of operation. The feed is dual-linear polarized, designed for a given half-angle, and is constructed entirely of aluminum except for the coaxial line center conductor and SubMiniature version A (SMA) connectors, which are gold-plated steel. The feed provides two SMA outputs, one for each linear polarization, which will be used to connect to the LNA section. We are actively collaborating with Sander Weinreb's group on the development of a scaled-up version of the

[2] A. Akgiray, "New Technologies Driving Decade-Bandwidth Radio Astronomy: Quad-Ridged Flared Horn & Compound-Semiconductor LNAs," PhD Dissertation, California Institute of Technology, 2013.

QRFH-HA-6-FL for operation in the 8–48 GHz range. In addition, we will upgrade the feed design so that the new design will use 2.4-mm connectors, which are suitable for operation up to 50 GHz.

We have pinned down the feed parameters and have begun iterative optimization of the feed design using a suite of codes including MATLAB, High-Frequency Structure Simulator (HFSS), Computer Simulation Technology (CST) Microwave Studio, and GRASP. For the purpose of this effort, the baseline antenna assumption is a version of the MeerKAT[3] antenna scaled to 18-m diameter. The assumed antenna is an offset Gregorian with an illumination angle of 50 deg. The following are the assumptions we made in order to proceed with the feed design:

- Antenna type: Offset Gregorian
- Feed design goals:
  - Return loss ≥ 20 dB
  - Cross-polarization ≥ 20 dB
  - F/D = 0.55
  - Efficiency = 55 percent
  - Output coaxial impedance = 50 Ω

Two methods for optimization of the feed are being used. The first uses MATLAB, which generates Python scripts for modifying the feed geometry in HFSS. A second approach uses MATLAB in conjunction with CST. Optimization of the feed patterns, taking into account spillover, LNA temperature, sky temperature, and illumination efficiency are ongoing. As a final check of feed performance, the patterns are used to illuminate the scaled MeerKAT antenna using GRASP. Figure 3(a) shows a drawing of the 8–48 GHz quad-ridge feed that we are currently studying. Figure 3(b) shows example radiation patterns obtained for this feed using our suite of simulation codes. Figure 3(c) depicts the MeerKAT antenna geometry. This version of the feed works excellently at lower frequencies, while its performance degraded slightly in the higher frequency band, due to some beam narrowing, as shown in the plots. We are also exploring adding a dielectric rod in the middle of the feed to improve its higher-frequency performance.

IV. Low-Noise Amplifier Design

During this effort, we also concentrated on the development of ultra-wideband LNAs at the chip level. We performed testing of 70-nm gallium arsenide (GaAs), metamorphic high-electron-mobility-transistor (mHEMT) MMIC LNAs that we obtained previously from the OMMIC foundry. These LNAs were tested in our laboratories and provided broadband performance with low noise temperature. Figure 4(a) shows a picture of an OMMIC LNA implemented for operation in the X-band. In Figure 4(b), one can observe the broadband

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[3] MeerKAT radio telecope, https://www.ska.ac.za/science-engineering/meerkat/

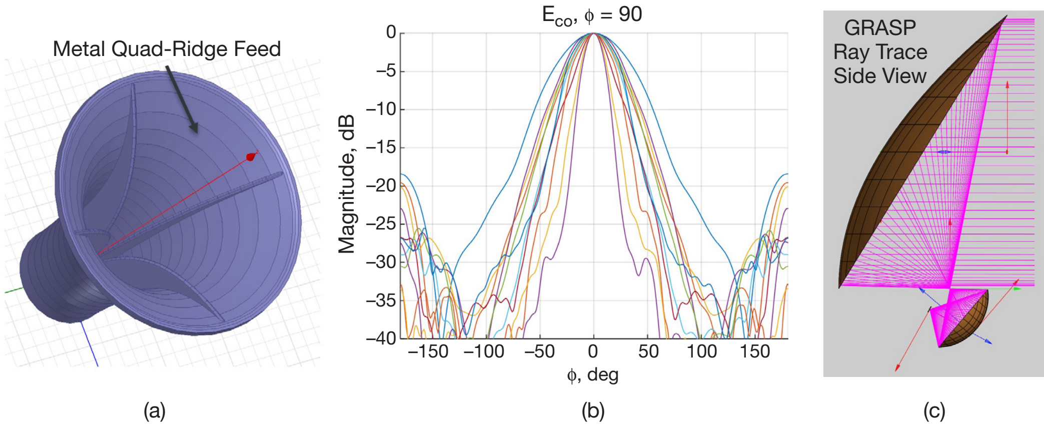


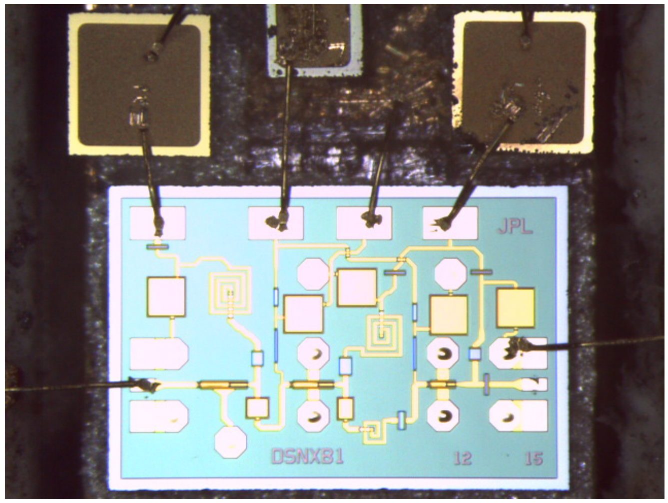
Figure 3. (a) Drawing of the 8–48 GHz feed antenna and (b),(c) performance of this antenna obtained with our suite of codes.

operation of these devices along the 1–18 GHz range. For instance, notice that at 8 GHz (DSN band), we obtained a noise temperature of 5.4 K, which is remarkable. We subsequently used the vendor's design kit to scale up the design of these LNAs to the 8–48 GHz range. Figure 5 shows an image of the as-designed 8–48 GHz, 1.5 mm × 1 mm, MMIC LNA. Also shown next to the MMIC is the corresponding LNA housing that we just completed. The LNA design shown in Figure 5 was based on simulations performed on Keysight's Advanced Design System (ADS). Typical ADS results are shown in Figure 6, where ~10 K noise temperature performance is obtained in the 8–30 GHz range. An order has been placed with OMMIC to fabricate this design. We expect to receive the OMMIC LNA wafers by the end of December 2016. Once we receive these devices, we will perform complete testing in our laboratories to assess their noise temperature and gain performance across the entire 8–48 GHz band.

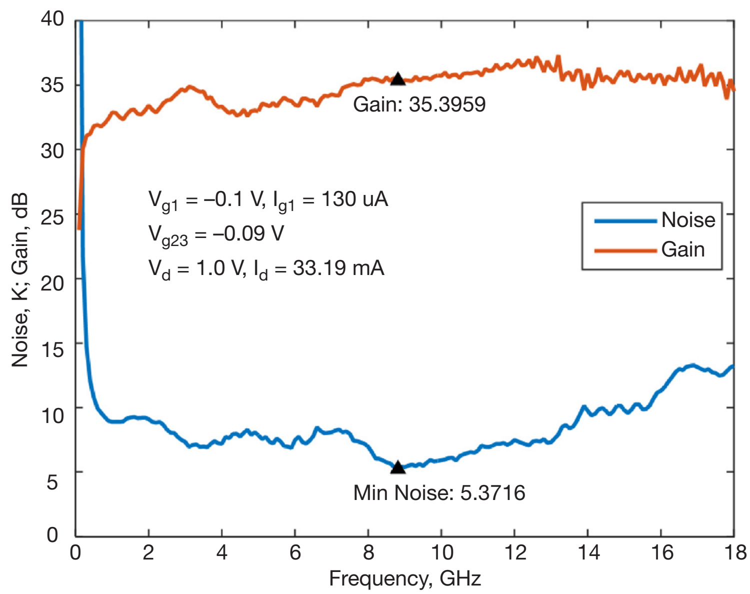
We are also investigating 35-nm indium phosphide (InP) HEMT LNAs fabricated by Northrop Grumman Company (NGC). We are basing our 8–48 GHz LNA design on the work carried out by Ahmed Akgiray [2]. We are currently using ADS to optimize the design of these devices. Results of this work will be reported as soon as they become available.

V. Noise Budget

As stated earlier, one of the goals of this effort is to develop a wideband receiver package with a maximum noise temperature of 35 K across the band. We have composed a noise temperature budget that includes the expected contributions of all the ultra-wideband receiver components. These components include the feed, dielectric rod, window, feed to LNA transmission line, LNA, and post-amplifier. This budget does not include the contribution of the downconverter components. In Table 1, we have tabulated the noise contribution of these components for four frequencies — 8, 15, 32, and 48 GHz. The receiver temperature, which includes all the components' contributions, is referred to as T_{rx}. Note that at the lowest frequency, T_{rx} = 19 K, whereas at the top of the frequency range, T_{rx} = 34 K. Noteworthy is the fact the main contributor to system noise is the LNA.



(a)



(b)

Figure 4. (a) Picture of 70-nm GaAs mHEMTs fabricated by OMMIC for operation in the 1–18 GHz range; (b) measured noise temperature and gain plots are shown as a function of frequency for the OMMIC LNA. Note that at 8.4 GHz, the measured noise temperature is 5.4 K.

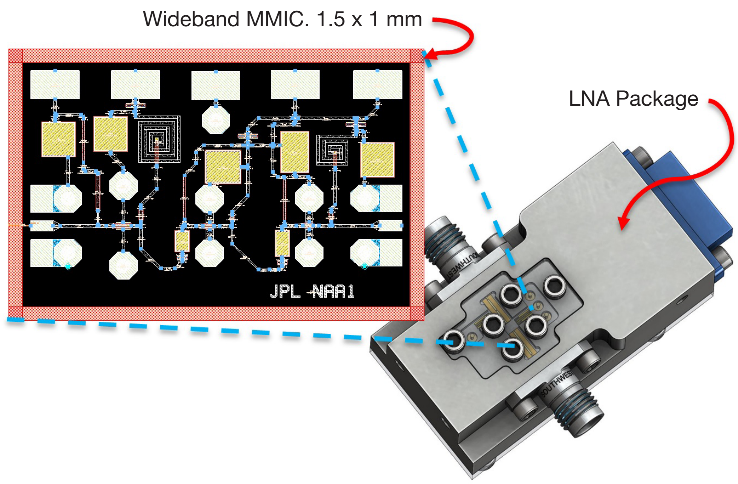


Figure 5. Schematic of OMMIC LNA housing package and MMIC LNA.

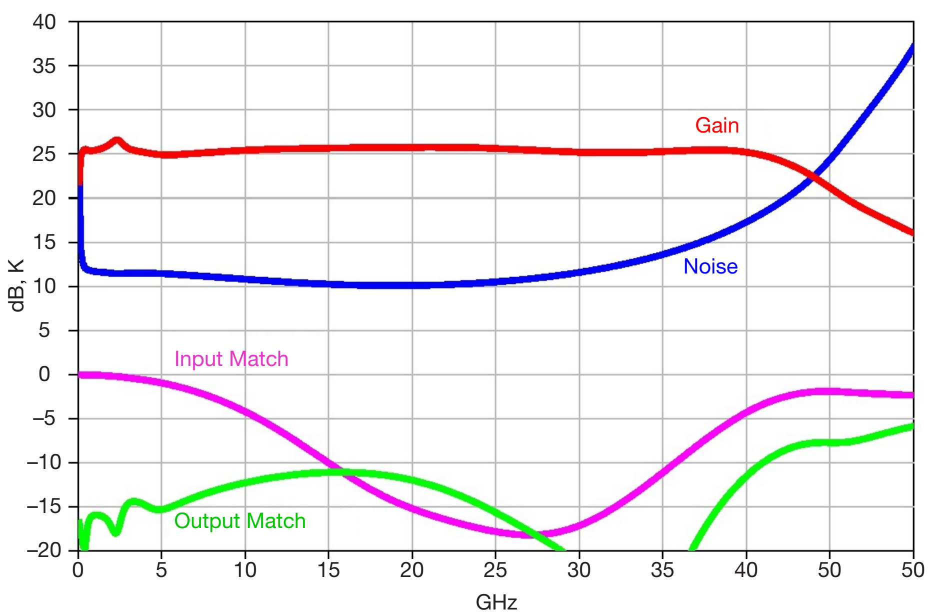


Figure 6. Simulation results of OMMIC LNA performance between 1 and 50 GHz for the LNA shown in Figure 5.

Table 1. Noise temperature budget.

Noise, K	At 8 GHz	At 15 GHz	At 32 GHz	At 48 GHz
Feed	1	2	3	3
Dielectric Rod	1	1	1	1
Window	3	3	3	3
Feed to LNA	1	2	3	3
LNA	12	12	12	20
Post-Amplifier	1	2	3	4
T_{rx}	**19**	**21**	**25**	**34**

VI. Conclusions

We have presented preliminary results of an 8–48 GHz ultra-wideband receiver development for the future North America Array. Results were presented for the feed design that were carried out via iterative optimization with our suite of codes. We are currently studying the insertion of a dielectric rod in the middle of the feed to improve feed performance at the higher frequency. Results of the feed optimization, including the dielectric rod, will be reported in future publications. We also reported on the 8–48 GHz LNA designs we are pursuing with 70-nm gallium arsenide mHEMTs from the OMMIC foundry and on 35-nm indium phosphide HEMTs manufactured by Northrop Grumman. Our initial receiver noise temperature calculations indicate that receiver operation below 35 K is possible. We plan to continue optimizing the LNA designs via simulations and testing with the goal of improving the receiver noise temperature, especially at the high-frequency end.

References

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[2] A. H. Akgiray, S. Weinreb, R. Leblanc, M. Renvoise, P. Frijlink, et al., "Noise Measurements of Discrete HEMT Transistors and Application to Wideband Very Low-Noise Amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 9, pp. 3285–3297, September 2013.